

Attachment A

Comparison of Servicing Mission Options (Prepared by Science Committee Staff)

	Advantages	Disadvantages
Shuttle Servicing Mission	<ul style="list-style-type: none">• Astronauts able to deal with unforeseen problems• Shortest development schedule• Demonstrated experience of four previous servicing missions	<ul style="list-style-type: none">• Safety Risk to Astronauts• Delay completion of ISS• Unknown cost and complexity to ready a second “rescue” shuttle• Shuttle-to-shuttle transfer of astronauts if rescue mission is launched• Unbudgeted cost to NASA
Robotic Servicing Mission	<ul style="list-style-type: none">• No safety risk to astronauts• Develop and test robotic technologies for future robotic exploration missions	<ul style="list-style-type: none">• Development and schedule risk• Limited ability to improvise repairs should unforeseen problems occur• Unbudgeted cost to NASA
Hubble Origins Probe (rehost)	<ul style="list-style-type: none">• No safety risk to astronauts• Has superior field of view than HST• Heritage design, several instruments already built	<ul style="list-style-type: none">• Science gap ~ two years or more• Unbudgeted cost to NASA
De-Orbit Mission (no servicing)	<ul style="list-style-type: none">• No schedule pressure. De-orbit not required before 2013.• Limited cost	<ul style="list-style-type: none">• No extended HST operations• Limited demonstration of robotic technologies

Attachment B

Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope

LOIUS J. LANZEROTTI, *Chair*, Consultant, Bell Laboratories, Lucent Technologies, and New Jersey
STEVEN J. BATTEL, Battel Engineering, Scottsdale, Arizona
CHARLES F. BOLDEN, JR., TechTrans International, Inc., Houston, Texas
RODNEY A. BROOKS, Massachusetts Institute of Technology Computer Science and Artificial Intelligence Laboratory, Cambridge, Massachusetts
JON H. BRYSON, The Aerospace Corporation (retired), Chantilly, Virginia
BENJAMIN BUCHBINDER, Consultant, Bonaire, Antilles
BERT BULKIN, Lockheed Missiles and Space (retired), Woodbridge, California
ROBERT F. DUNN, U.S. Navy (retired); National Consortium for Aviation Mobility, Alexandria, Virginia
SANDRA M. FABER, University of California Observatories/Lick Observatory, University of California, Santa Cruz
RICCARDO GIACCONI, Johns Hopkins University and Associated Universities, Inc., Washington, D.C.
GREGORY HARBAUGH, Sun N Fun Air Museum, Lakeland, Florida
TOMMY W. HOLLOWAY, NASA (retired), Houston, Texas
JOHN M. KLINEBERG, Space Systems/Loral (retired), Redwood City, California
VIJAY KUMAR, University of Pennsylvania, Philadelphia, Pennsylvania
LT GEN FORREST S. MCCARTNEY, U.S. Air Force (retired), Indian Harbour Beach, Florida
STEPHEN M. ROCK, Stanford University, Stanford, California
JOSEPH H. TAYLOR, JR., Princeton University, Princeton, New Jersey
ROGER E. TETRAULT, McDermott International, Inc. (retired), Punta Gorda, Florida
VADM RICHARD H. TRULY, U.S. Navy (retired); National Renewable Energy Laboratory, Golden, Colorado

Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope Statement of Task

The committee will conduct an independent assessment of options for extending the life of the Hubble Space Telescope. The study will address the following tasks:

1. Assess the viability of a space shuttle servicing mission that will satisfy all recommendations from the CAIB (Columbia Accident Investigation Board), as well as ones identified by NASA's own Return-to-Flight activities. In making this assessment, compare the risks of a space shuttle servicing mission to HST with the risks of a shuttle mission to the ISS and, where there are differences, describe the extent to which those differences are significant. Estimate to the extent possible the time and resources needed to overcome any unique technical or safety issues associated with HST servicing that are required to meet the CAIB recommendations, as well as those from the Stafford-Covey team.
2. Survey other available engineering options, including both on-orbit robotic intervention and optimization of ground operations, that could extend the HST lifetime.
3. Assess the response of the spacecraft to likely component failures and the resulting impact on servicing feasibility, lost science, and the ability to safely dispose of HST at the end of its service life.
4. Based upon the results of the tasks above, provide a benefit/risk assessment of whether extension of HST service life, via (a) a shuttle servicing mission if one is deemed viable under task #1 and/or (b) a robotic servicing mission if one is deemed viable under task #2, is worth the risks involved. The assessment should include consideration of the scientific gains from different options considered and of the scientific value of HST in the larger context of ground and space-based astronomy and science more broadly. Special

attention should be paid to the practical implications of the limited time available for meaningful intervention robotically or via the shuttle.

The committee is not expected to make either organization or budgetary recommendations, but it may need to consider cost as a factor in weighing the relative benefits of alternative approaches.

The committee will investigate the possibility of providing an interim report to NASA that addresses a portion of the items in the task statement in advance of delivering a full final report if such an approach is deemed feasible and able to provide early, credible answers to the questions being considered.

Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope

Recommendations

1. The committee reiterates the recommendation from its interim report that NASA should commit to a servicing mission to the Hubble Space Telescope that accomplishes the objectives of the originally planned SM-4 mission.
2. The committee recommends that NASA pursue a shuttle servicing mission to HST that would accomplish the above stated goal. Strong consideration should be given to flying this mission as early as possible after return to flight.
3. A robotic mission approach should be pursued solely to de-orbit Hubble after the period of extended science operations enabled by a shuttle astronaut servicing mission, thus allowing time for the appropriate development of the necessary robotic technology.

Findings

Chapter 3 – The Impact of Hubble: Past and Future

- The Hubble telescope is a uniquely powerful observing platform because of its high angular optical resolution, broad wavelength coverage from the ultraviolet to the near infrared, low sky background, stable images, exquisite precision in flux determination, and significant field of view.
- Astronomical discoveries with Hubble from the solar system to the edge of the universe are one of the most significant intellectual achievements of the space science program.
- The scientific power of Hubble has grown enormously as a result of previous servicing missions.
- The growth in the scientific power of Hubble would continue with the installation of the two new instruments, Wide Field Camera-3 (WFC3) and the Cosmic Origins Spectrograph (COS), planned for SM-4.
- A minimum scientifically acceptable servicing mission would install batteries, gyros, WFC3, and a FGS. The installation of COS is highly desirable.
- Ground-based adaptive optics systems will not achieve Hubble's high degree of image stability or angular resolution at visible wavelengths for the foreseeable future.
- Servicing Hubble expeditiously is highly desirable.

Chapter 4 – HST Observatory Assessment and Lifetime Projection

- The HST avionics system is currently in a fully operable state and retains redundancy on all subsystems. Its performance is monitored regularly and is well understood by the operations team where it is possible to credibly forecast system performance, failure trends, and replacement requirements.
- Previous human servicing missions have successfully carried out unforeseen repairs as well as executing both planned and proactive equipment and scientific upgrades. The current excellent operational status of the observatory is a product of these past efforts.
- The robotic mission plan presented by NASA accomplishes the minimum mission servicing goals of installing batteries, gyros, and scientific instruments and potentially a fine-guidance sensor, but does not install other important life-extension upgrades that were also planned for SM-4. It is also unclear whether the fine guidance sensor replacement or unforeseen repairs can be effected on a robotic mission without exceptional mission complexity and associated telescope risk.
- The HST avionics system reliability model used by NASA projects a 50 percent reliability interval of 4.5 years. Using October 2004 as a starting date, this interval establishes May 2009 as the latest approximate date for vehicle servicing with at least a 50 percent chance for success.
- The flexibility for repairing unforeseen anomalies has been demonstrated on past shuttle servicing mission. With this flexibility, the avionics system is projected to operate with a reliability value of 0.69 at 3 years and 0.45 at 5 years in support of science operations following a shuttle servicing mission.
- The baseline robotic mission is judged to have minimal capacity for responding to and repairing unforeseen anomalies. Assuming robotic servicing in February 2009 (based on a 5.4 year “most likely” readiness date), the system reliability is projected to be 0.41 at the time of servicing, 0.18 after 3 years of post-servicing science operations, and less than 0.10 at 5 years.
- Battery lifetime trends are consistent with supporting science operations through April 2008 and maintaining the telescope optical system in a highly protected Level-1 safe-hold state until July 2009. Loss of capability to do science due to optical failure is most likely to occur in the May 2011 timeframe but could occur as early as December 2009 based on a worst-case projection.
- If HST operations continue as they are, progressive gyroscope failures are likely to terminate observatory science operations around September 2007. Timely transition to a 2-gyro mode after software validation in the first half of 2005 could extend science operations into the mid-2008 timeframe.
- HST gyro replacement by the shuttle is a straightforward operation that has been accomplished successfully on past servicing mission. Replacement by a robotic mission is more complex, entailing the attachment of multiple RSU and ECU elements plus interface electronics on to the WFC3 instrument. The interface to the spacecraft system is made via an external cable routed to a test interface on the telescope computer.
- FGS-2R is projected to fail in the October 2007 to October 2009 timeframe. Its replacement is important if FGS redundancy is to be retained to support post-servicing science operations. Replacement of FGS-2R is straightforward on a shuttle mission but considered to be high risk for a robotic mission. Therefore, it is possible to retain FGS redundancy by shuttle servicing and potentially is possible via robotic servicing.
- FGS-3 is projected to fail in the January 2010 to January 2012 timeframe although its life can potentially be extended through the near-term use of FGS-2R. Failure in this timeframe will not strongly affect post-servicing science operations if FGS-2R is replaced.

- Solar Panel performance is running according to expected trends such that sufficient power will be available to support HST science operations until at least 2014 in the case of either shuttle or robotic servicing.
- Retention of Reaction Wheel Assembly redundancy is important to maximize the likelihood of 3 to 5 years of post-servicing HST science operations. Replacement of RWA units has been performed successfully in response to an unexpected anomaly on two previous shuttle mission and is also possible, if required, on SM-4. Replacement of an RWA is not part of the planned robotic mission and may not be possible due to the RWA mounting locations on the telescope.
- Analysis in combination with long-term avionics monitoring predicts that radiation damage should not interfere with science operations through the 2010 timeframe. Adverse radiation effects after 2010 are more likely, with an increasing risk of avionics component failures if science operations are extended until 2014.
- The projected termination in mid to late 2007 of science operations due to gyroscope failure and the projected readiness in early 2010 to execute the planned NASA robotic mission result in a projected 29-month interruption of science operations. No interruption of science operations is projected for a realistically scheduled SM-4 shuttle mission.
- The planned NASA robotic mission is less capable than the previously planned SM-4 mission with respect to its response to unexpected failures and its ability to perform proactive upgrades. Combined with the projected schedule for the two options, the mission risk associated with achieving at least 3 years of successful post-servicing science operations is significantly higher for the robotic option with the respective risk numbers at 3 years being approximately 30 percent for the SM-4 mission and 80 percent for the robotic mission.

Chapter 5 – HST Robotic Servicing Assessment

- The technology required for the proposed HST robotic servicing mission involves a level of complexity, sophistication, and maturity that requires significant development, integration, and demonstration to reach flight readiness and has inherent risks that are inconsistent with the need to service Hubble as soon as possible.
- Technologies needed for proximity operations and autonomous rendezvous and capture have not been demonstrated in a space environment.
- The addition of targets and fiducials and a better latching system by the astronauts on the SM-4 mission will enhance the ability of the subsequently launched de-orbit module to dock with the HST and provide a more precise alignment for de-orbit.
- The control algorithms and software for lidar and camera based control of the grapple arm are mission-critical technologies that have not been flight-tested.
- Technologies needed for autonomous manipulation, disassembly and assembly, and for control of manipulators based on vision and force feedback have not been demonstrated in space.
- The Goddard Space Flight Center HST project has a long history of HST shuttle servicing experience, but little experience with autonomous rendezvous and docking or robotic technology development, or with the operations required for the baseline HST robotic servicing mission.
- The proposed HST robotic servicing mission involves a level of complexity that is inconsistent with the current 39-month development schedule and would require an unprecedented improvement in development performance compared with that of space missions of similar complexity. The likelihood

of successful development of the HST robotic servicing mission within the baseline 39-month schedule is remote.

- **“Conclusion”**: The very aggressive schedule for development of a viable robotic servicing mission, the commitment to development of individual elements with incomplete systems engineering, the complexity of the mission design, the current low level of technology maturity, the magnitude of the risk-reduction efforts required, and the inability of a robotic servicing mission to respond to unforeseen failures that may well occur on Hubble between now and the mission, together make it unlikely that NASA will be able to extend the science life of HST through robotic servicing. (page 74).
- Many of the concerns raised by the committee regarding the risk of attempting to robotically service the Hubble telescope could be mitigated for future programs through planning for robotic servicing in the initial spacecraft design.

Chapter 6 – Space Shuttle Servicing of Hubble

- A complete inspection of the orbiter thermal protection system can be accomplished on a shuttle servicing mission to HST using the SRMS (shuttle remote manipulator system) and the SRMS/OBSS (orbiter boom sensor system).
- The orbiter thermal protection system repairs can be accomplished on a shuttle servicing mission to HST following the development of worksite and repair techniques for ISS (International Space Station) to meet the CAIB (Columbia Accident Investigation Board) and NASA requirements.
- The ISS safe haven offers operational flexibility and time to adapt to real-time problems in the case of a critical ascent impact event that is both detected and repairable, or that affords the option of a shuttle rescue mission. However, the availability of the ISS safe haven is zero-fault-tolerant, requires significant pre-positioning of supplies, and therefore, has significant risks due to its limited redundancy and margins.
- An HST shuttle rescue mission can be ready on the second launch pad. There would be some costs and ISS schedule delays, principally because of the impact of parallel orbiter processing. Limited time would be available to execute a rescue.
- Meeting the CAIB and NASA requirements (relative to inspection and repair, safe haven, shuttle rescue, orbital debris, and risk to the public) for a shuttle servicing mission to HST is viable.
- The extravehicular activities (spacewalks) for transferring the crew from a damaged vehicle on a shuttle HST flight, although complex, are well within the experience base of the shuttle program.
- To avoid putting the Hubble at risk and to maintain continuous science operation the HST servicing mission could be flown as early as the seventh flight after return to flight without a critical operational impact on the ISS.
- Major HST mission preparation work for a shuttle servicing mission to HST can be deferred until after return to flight. This would avoid a significant expenditure of human resources until the shuttle is flying again.
- Compared to the total cost of flying a shuttle flight, the resources required to overcome unique technical or safety issues involved in flying a shuttle mission to HST are small and are well within the experience base of work done in the past to enable unique shuttle missions.
- **“Comment”**: The committee believes that careful planning for, and implementation of, the additional HST-unique activities to meet the CAIB and NASA requirements will result in substantially lower

actual costs to service the HST using the shuttle than those projected above. [NASA estimates of \$1.7B - \$2.4B.] (Page 87).

- The shuttle crew safety risks of a single mission to ISS and a single HST mission are similar and the relative risks are extremely small.
- In the case of every documented anomaly encountered during the conduct of extravehicular activities (EVAs) on all four HST missions, the onboard crew, in conjunction with its ground-based mission control team, worked around each anomaly and successfully completed every task planned for these missions.
- Space shuttle crews, in conjunction with their ground-based mission control teams, have consistently developed innovative procedures and techniques to bring about desired mission success when encountering unplanned for or unexpected contingencies on-orbit.
- The risk in the mission phase of a shuttle HST servicing mission is low.

Chapter 7 – Benefit/Risk Assessment of Hubble Space Telescope Servicing Options

- Although a quantitative mission risk assessment does not exist for either a human or a robotic servicing mission to the Hubble Space Telescope, the committee's qualitative evaluations lead it to conclude that the human servicing mission poses a low risk to mission success. Conversely, the robotic mission risk is high, considering the short time frame available for system development and testing, and the uncertainty concerning robotic performance.